

Simultaneous MEG and EEG source analysis

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1 Introduction

A method is described to jointly estimate source and head parameters in a simultaneous MEG and EEG analysis. This simultaneous analysis would be very beneficial if it can be shown that it profits from the advantages of both modalities [e.g. 1].

First, the highest spatial gradients, and thus the preferred directions, differ between MEG and EEG. It is expected that both directions are precise in a simultaneous analysis. Second, deep sources hardly generate a MEG signal. Therefore source precision deteriorates fast with depth. It is expected that this disadvantage is countered in a simultaneous analysis. Third, the precision of superficial sources is higher for MEG than for EEG. It is expected that a simultaneous analysis profits from this advantage. Fourth, the radial component of a dipole cannot be estimated from MEG. It is expected that this component can be estimated reliably in a simultaneous analysis. Fifth, EEG requires accurate information concerning the radii and conductivities. This is problematic, since these parameters are not known precisely. A combined analysis may offer a solution to this problem, since it allows for the joint in vivo estimation of source and head parameters.

2 Methods

The regression model is:

$$\begin{bmatrix} \mathbf{y}_m \\ \mathbf{y}_e \end{bmatrix} = \begin{bmatrix} \mathbf{F}_m(\mathbf{X}_m, \mathbf{Z}_m, \boldsymbol{\tau}) \\ \mathbf{F}_e(\mathbf{X}_e, \boldsymbol{\tau}, \boldsymbol{\alpha}, \boldsymbol{\beta}) \end{bmatrix} \boldsymbol{\xi} + \begin{bmatrix} \boldsymbol{\varepsilon}_m \\ \boldsymbol{\varepsilon}_e \end{bmatrix}$$

The subscripts indicate values differing between MEG and EEG. $\mathbf{y}$: measurements on N sensors; $\mathbf{F}$: nonlinear part of the MEG or EEG model in concentric spheres; $\mathbf{X}$: sensor locations; $\mathbf{Z}$: sensor orientations; $\boldsymbol{\tau}$: source locations; $\boldsymbol{\xi}$: source moments; $\boldsymbol{\alpha}$: radii; $\boldsymbol{\beta}$: conductivities; $\boldsymbol{\varepsilon}$: noise distributed with zero mean and covariance matrix $\mathbf{V}$. The parameters are collected in $\boldsymbol{\theta}' = [\boldsymbol{\tau}', \boldsymbol{\xi}', \boldsymbol{\alpha}', \boldsymbol{\beta}']$.

The MEG model for sensor n and dipole d is given by $\mathbf{b}(\mathbf{x}_n, \boldsymbol{\tau}_d, \boldsymbol{\xi}_d)' \mathbf{z}_n' / (\mathbf{z}_n' \mathbf{z}_n)^{1/2}$, where $\mathbf{b}(\mathbf{x}_n, \boldsymbol{\tau}_d, \boldsymbol{\xi}_d)$ is the vector valued magnetic field [2]. The EEG

model is given in [3], where appropriate rotations are implemented for dipoles off the z-axis [cf. 4], and where the reference is explicitly taken into account.

Source and head parameters are estimated by generalized least squares (GLS) to account for unequal noise variances and nonzero noise correlations. If only MEG is analyzed, then the radial dipole component cannot be estimated. Therefore each source has to satisfy the constraint that it is tangential. It may also be useful to impose constraints on head parameters. First, radii can be fixated on known values, for example obtained from an MRI scan. Second, if only EEG is analyzed, then conductivities have to be fixated on assumed values. Third, if conductivities are estimated, then it can be imposed that cortex and fluid conductivity is equal, or that cortex and scalp conductivity is equal.

In sum, source and head parameters are estimated by minimizing the GLS function subject to one or more of the following constraints:

$$\begin{aligned} \hat{\boldsymbol{\tau}}_d' \hat{\boldsymbol{\xi}}_d &= 0 && \text{sources should be tangential for MEG.} \\ \hat{\alpha}_j &= \alpha_j && \text{assume a conductivity for the } j\text{'th sphere.} \\ \hat{\beta}_j &= \beta_j && \text{assume a radius of the } j\text{'th sphere.} \\ \hat{\beta}_j &= \hat{\beta}_k && \text{conductivity of sphere } j \text{ and } k \text{ is equal.} \end{aligned}$$

The covariance matrix of the parameter estimates should be corrected for the constraints [5]. The first order partial derivatives of the K constraint functions to the P parameters are collected in the K by P matrix $\mathbf{L}$. The first order partial derivatives of the N modeled signals to the P parameters are collected in the N by P matrix $\mathbf{G}$. Then the covariance matrix of the parameter estimates is given by the P by P left upper part of [5]:

$$\begin{bmatrix} \mathbf{G}'\mathbf{V}^{-1}\mathbf{G} + \mathbf{L}'\mathbf{L} & \mathbf{L}' \\ \mathbf{L} & \mathbf{O} \end{bmatrix}^{-1} \quad (1)$$

3 Results

3.1 Design of the simulation study

Five configurations are compared. 127 MEG and 127 EEG are used to study the effects of MEG and EEG under optimal spatial sampling conditions. 127 MEG+127 EEG is used to study the effects of a combined analysis. 61 MEG+61 EEG is used to exclude the possibility that a combined analysis is only beneficial due to an increased spatial sampling. 127 MEG+19 EEG is used to study whether the disadvantages of MEG can be countered by measuring only a few extra EEG sensors.

Each configuration covers the entire upper hemisphere [cf. 4]. The head is modeled as four concentric spheres with radii 8.98, 9.21, 9.66, and 10.0 cm and isotropic conductivities .33, 1.0, .0042, and .33 (Ωm)⁻¹ [cf. 4]. The noise standard deviation is equal within modalities and noise is uncorrelated within and between modalities. The MEG or EEG noise standard deviation is 10% of the maximum MEG or EEG signal generated by the tangential source at an eccentricity of .7 on the 127 sensor configuration [cf. 4].

We performed Monte Carlo simulations to check whether the standard errors obtained from eq. 1 are valid indicators of precision. This was almost always the case, except where indicated otherwise. If the standard errors are not a valid indicator, then we report the simulation results. Namely, the location error: the average Euclidean distance between true and estimated location vectors; and the moment error: the average Euclidean distance between true and estimated moment vectors.

3.2 Results

Tangential source, known conductivities

There are several pronounced differences between MEG and EEG (Fig. 1). First, the preferred location directions are transverse (across dipole location and moment) for MEG and longitudinal (along dipole orientation) for EEG. The preferred moment direction is transverse for both MEG and EEG. Second, the accuracy of all MEG parameters, except transverse location, is very much affected by eccentricity, whereas the accuracy of all EEG parameters is only slightly affected. Third, transverse location is at all eccentricities more precise for MEG than for EEG. Moreover at eccentricities $\geq .7$ the other location parameters are also slightly more precise for MEG. The EEG moment parameters are always superior to MEG.

The advantages of EEG and MEG carry over to 127 MEG+127 EEG. First, transverse location is precise due to MEG and longitudinal location is precise due to EEG. Second, there are only minor effects of eccentricity. Third, superficial sources profit from accurate MEG location and accurate EEG moment, and deep sources profit from accurate EEG location and moment.

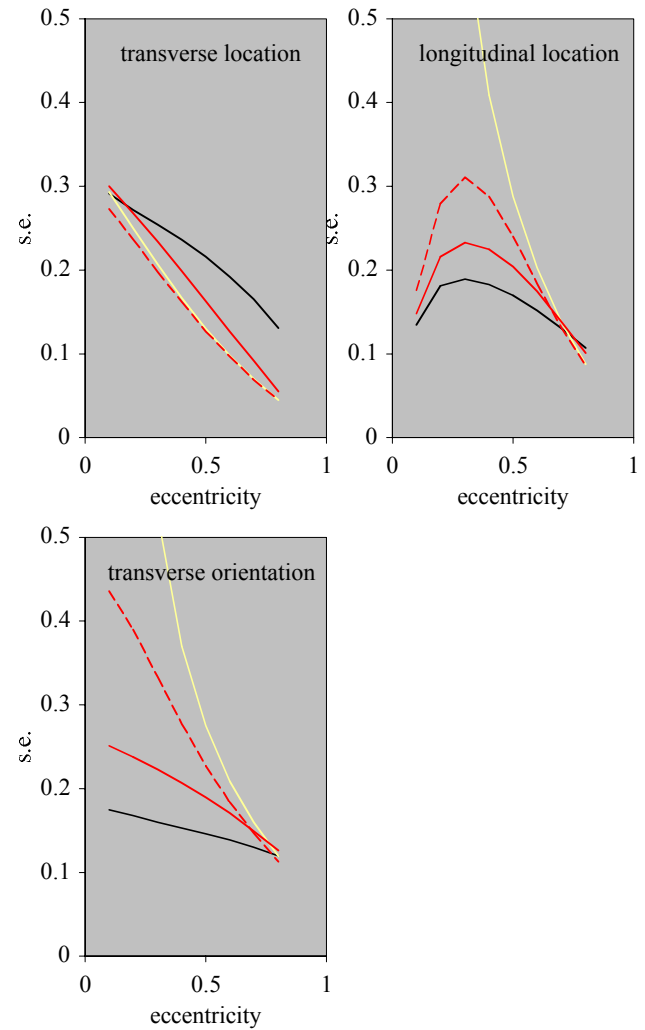


Figure 1: The parameter standard errors at different eccentricities. The standard errors are multiplied by the radius of the sphere, $r=10$: the unit of the location errors is cm, and the unit of the moment errors is dAm. — : 127 EEG; - - - : 127 MEG; — : 61 MEG + 61 EEG; - - - : 127 MEG + 19 EEG

61 MEG+61 EEG yields in general a precision approaching the precision of 127 MEG+127 EEG, indicating that the advantages of a simultaneous

analysis are not only due to an increase in the number of sensors. Adding 19 EEG sensors to 127 MEG is also favorable, since it reduces the disadvantageous effects of MEG, namely imprecise estimates of deep sources and inaccurate moment estimates.

Partially radial source, known conductivities.

The radial moment estimate is biased for MEG, therefore its standard error is not a valid indicator of precision. Hence we report the location and moment errors in Table I. It can be seen that the moment error is very large for MEG, whereas it is small in the simultaneous conditions. Note that even adding only 19 EEG sensors yields a significant improvement.

Table I: *The location and moment errors of the radial source. All quantities are multiplied by the radius of the sphere, $r=10$. In this manner the unit of the location errors is cm, and the unit of the moment errors is dAm.*

	Location	Moment
127 EEG	.24	.24
127 MEG	.26	5.03
61 MEG + 61 EEG	.22	.29
127 MEG + 19 EEG	.24	.43

Tangential source, estimated conductivities

Source and conductivity parameters are estimated from 127 MEG+127 EEG. Radii parameters are known, namely 8.98, 9.21, 9.66, and 10.0.

First, we analyze the tangential source at an eccentricity of .7 in the three shell model with conductivities .33, .33, .0042, .33. Conductivities are estimated under the constraint that cortex, fluid and scalp conductivity is equal. The standard errors of the conductivity estimates are low (.025, .025, .001 and .025), indicating that these parameters can be estimated reliably. In Fig. 2 it can be seen that the standard errors of the source parameters are equal to those obtained given known conductivities, except for an increase in the standard error of radial location and longitudinal moment.

Second, we analyze the tangential source at an eccentricity of .7 in the standard four shell model. Conductivities are estimated under the constraint that cortex and scalp conductivity is equal. The conductivity parameters are biased: only in about 50% of the simulation replicates the mean estimated fluid conductivity equals its true value, in the other replicates it resembles skull conductivity. However, this does not affect source precision: all source parameters are unbiased, and conductivity

estimation again only affects the precision of radial location and longitudinal moment (Fig. 2).

a.s.e. (cm/dAm)

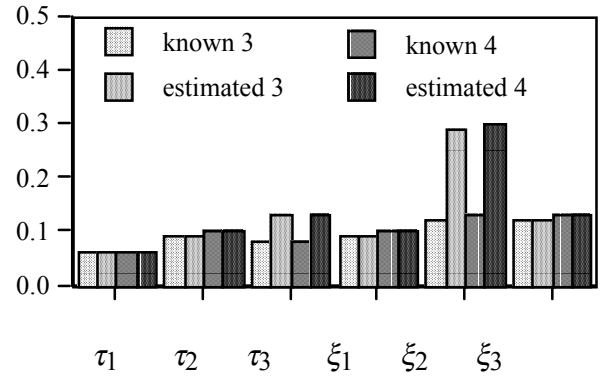


Figure 2: *The standard error (a.s.e.) of the source parameters given known or estimated conductivities in the 3 or 4 shell model. The source parameters denote: transverse, longitudinal, and radial location and transverse, longitudinal, and radial moment. All quantities are multiplied by $r=10$: the unit of the location errors is cm, the unit of the moment errors is dAm.*

Finally, to illustrate the merits of conductivity estimation, we simulate data given the standard four conductivities, whereas sources are estimated given an alternative set of conductivities [6], namely .13, 1.0, .0070, and .05. In Table 2 it can be seen that the location and moment errors are much higher than the errors obtained from estimated conductivities.

Table 2: *Location and moment errors given known, estimated or incorrect conductivities. All quantities are multiplied by $r=10$: the unit of the location errors is cm, the unit of the moment errors is dAm.*

	Location	Moment
Known conductivities	.14	.21
Estimated conductivities	.15	.29
Incorrect conductivities	.52	4.34

Tangential source, realistic head, estimated conductivities

In this section we investigate whether conductivity estimation in concentric spheres is also beneficial if data are generated in a realistic model. The realistic model is divided in three compartments with conductivities of .33, .0042 and .33. The tangential source at an eccentricity of .7 is used to simulate a signal on the 127 EEG + 127 MEG sensors. The radii of the 2 inner spheres are set to the standard values of 92.1% and 96.6% of the estimated outer spheres radius.

Three situations are compared: source estimates given known conductivities (.33, .0042 and .33); joint estimation of source and conductivity parameters, where the conductivity of the cortex and the scalp is not constrained to be equal; source estimates given the alternative set of conductivities (.13, .0070, and .05). Conductivity estimation yields more precise source estimates than an analysis based on known conductivities (Table 3). This indicates that conductivity estimation can compensate for the difference between standard and actual radii. Moreover conductivity estimation again yields more precise estimates than an analysis based on incorrect conductivities (Table 3).

Table 3: Data generated in a realistic head model. Location and moment errors given known, estimated or incorrect conductivities. All quantities are multiplied by $r=10$: the unit of the location errors is cm, the unit of the moment errors is dAm.

	Location	Moment
Known conductivities	.32	3.00
Estimated conductivities	.32	.33
Incorrect conductivities	1.74	4.00

4 Discussion

A simultaneous MEG and EEG analysis has several advantages. First, it profits from the preferred location directions of MEG and EEG. Since the preferred moment directions do not differ between EEG and MEG, a simultaneous analysis has no additional benefits in this respect. Second, there are only minor effects of eccentricity. Third, superficial sources profit from accurate MEG location and EEG moment, and deep sources from accurate EEG location and EEG moment. Fourth, the radial component can be estimated. And fifth, the conductivities can be estimated, which increases precision greatly.

It is shown that conductivity estimation only affects the precision of radial location and longitudinal moment. Moreover it is shown that conductivity estimation is even recommended if the conductivity parameters are not identified appropriately. For example, it appeared that cerebrospinal fluid conductivity could not be differentiated from skull conductivity, but that this did not affect source precision.

These advantages of a simultaneous analysis are not only due to an increased spatial sampling. 61 MEG+61 EEG should also be preferred to either 127 MEG or 127 EEG. Moreover, adding 19 sensors to

127 MEG greatly reduces the disadvantageous properties of MEG.

Acknowledgements

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